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Climate Change Impacts on Financial Risk in Hydropower Projects

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Abstract**-- Limiting the emissions of greenhouse gases from power generation will depend, among other things, on the continuing and increased use of hydroelectric power. However, climate change itself may alter rainfall patterns, adversely affecting the financial viability of existing and potential hydro schemes. Previous work developed a methodology for quantifying the potential impact of climate change on the economics of hydropower schemes. Here, the analysis is extended to examine the potential for changes in project risk. A case study is presented that indicates that the applied climate change scenarios alter not only the mean financial performance of the scheme but also the financial risk facing it. Given that investors must balance project risk and reward, this finding has implications for the future provision of hydropower.**

Index Terms**-- hydroelectric power generation, hydrology, meteorology, finance, risk analysis.**

I. Introduction

LIMITING and, even reversing, rising greenhouse gas levels depends implicitly on the continued and increased use of hydroelectricity. There are suggestions that hydro production may increase by up to three times over the twenty-first century [1]; forecasts of rising electricity demand and likely fossil-fuel price rises support such projections but do not offer guarantees.

Deregulation of the electricity industry means that, more than ever, the economics of competing generation technologies will determine which contribute to supply. A preference for low capital-cost, faster payback options does not favour hydro. The outlook worsens when the effects of changes in climate are considered, such as reduced river flows and lower hydroelectric output. Such outcomes would reduce financial returns and make hydropower less competitive [2].

II. Variable Returns

Previous work examined how the application of climate model-derived climate change scenarios impacted on the financial performance of a proposed hydro scheme [3]. Further, a sensitivity study was performed to indicate the extent to which the scheme could tolerate changes in precipitation and temperature [4]. Both studies found that changes in climate led to significant variations in scheme economic performance. Furthermore, it was found that in addition to altering mean values of river flows and production, there were also changes in their variance. This consequently altered the variability of electricity sales income, which was identified as being potentially problematic in cash flow terms.

Such changes in variance have been noted previously in studies investigating the hydrological effects of climate change. There is a tendency for river basins to amplify changes in precipitation, resulting in larger changes in river flows than in precipitation [5]. This non-linearity is responsible for altering flow variance as well as mean flows. The effect is illustrated in Fig. 1.

Given the changes in production and revenue variance, the authors considered it prudent to examine, more closely, the impacts on variability and, in particular, the impact on the variability of the financial return, i.e., the project risk.

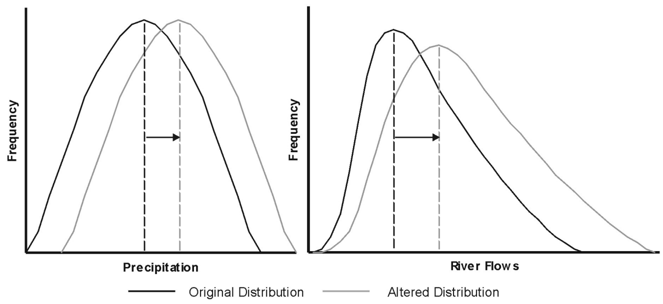

Fig. 1. Effect of river basin in altering river flow variance with changes in mean precipitation (adapted from [5]).

III. Quantifying Risk

Risk is notoriously difficult to quantify and its estimation is often rather subjective. Payback period is commonly used as a proxy for risk, with longer periods implying greater risk [6]. While this has merit, the use of payback period as an investment indicator is often criticised as it fails to discount cash flows. Sensitivity analysis provides a simple means of indicating project risk with greater risk implied by greater sensitivity to a given variable. Its limitations are that it views variables in isolation where, in fact, their combined effect may be greater. It also fails to provide information on the probability of outcomes [7]. In analysing hydroelectric projects, it relies on the results from a single time-series of river flows or, as in climate impact studies, precipitation and temperature. Given that the timing of dry or wet periods

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influences production and economic projections, predictions can be overly optimistic or pessimistic. This is particularly true with analyses employing discounting methods, which place greater emphasis on earlier time periods. The use of risk analysis techniques can remove some of these limitations.

Risk analysis techniques are established in hydropower applications and are primarily based on the use of synthetic river flow series. Statistically identical to the original series, the synthetic series provide alternative sequences of flows that may be used to examine the robustness of scheme operating regimes [8] or the range of financial outcomes. Monte-Carlo simulations of project costs and benefits have also found use in hydropower applications, e.g. [9]. So far, risk techniques have found only limited application in climate change studies. A notable exception was the use of synthetic climate series to assess the reliability of production from hydroelectric stations in central Greece [10]. The work described here extends the analysis to project economics and the implications of changing risk on the preferences of would-be investors.

Financial risk is an expression of the variance of the returns from a particular investment. Where returns do not vary from the expected value (i.e. zero variance) the investment is regarded as risk-free (e.g. Government Bonds). However, most other investments are not risk-free and rational investors require a higher rate of return (or risk premium) to compensate them for the risk. This principle is the basis of the Capital Asset Pricing Model (CAPM) which describes the relationship between the required return from an equity stock, and risk of the equity and the market as a whole [11]:

$$r_e = r_f + \beta(r_m - r_f) \tag{1}$$

Here, r_f and r_m are, respectively, the risk-free and market rates of return, r_e is the required rate of return for the equity, and β the equity 'beta'. The beta is the relative risk of the equity compared to the market as a whole, and a β greater than 1 indicates that the stock is more risky than the market average. Normally determined by a regression of equity returns against a proxy for the market returns (e.g. FTSE 100), it is given by:

$$\beta = \frac{\sigma_e}{\sigma_m}\rho \tag{2}$$

where σ_e and σ_m are the standard deviations of the equity and market returns and ρ is the coefficient of correlation between them. Hence, a change in the variance of returns or financial risk of the equity will alter the expected return.

The same principles can also be applied to the appraisal of individual projects by relating the variance of financial returns, i.e. the internal rate of return (IRR), to the project beta and hence to the required rate of return. The required rate of return from a project is the minimum acceptable to an investor and is used as the discount rate to determine project net present value (NPV). Through the project beta, the risk associated with a project may directly influence the discount rate and the eventual investment decision, perhaps critically so. Therefore, the alteration of the project risk profile through changes in climate may affect the competitiveness of hydroelectric projects and analysis of this aspect is of importance.

IV. Investment Risk Model

The investment risk model presented here is an extension of software developed by the authors. The software has a series of components including hydrological, reservoir, market and financial models that allow the projection of river flows, energy production and financial performance from applied climate scenarios. The original software is described in detail in [3] while a summary is given below.

A. *Original Simulation Tool*

The model operates on a monthly time-step and is driven by monthly time series of climate data including precipitation, temperature and other necessary variables. An original aim of the work was to produce a working and verifiable model that could provide an initial quantitative estimate of climate impact, using the minimum level of complexity. As such, each component is relatively simple in concept and implementation.

The hydrological model translates climatic inputs into estimates of river flow. The simple water balance model used considers the river basin as a single storage unit, with precipitation as inflow and evaporation and river flows as outflows (where outflows are functions of water in storage).

The reservoir model determines the energy production arising from the inflow subject to the operating rules. Again using a mass balance approach, the operational objective is to attain specified monthly production targets whilst satisfying storage, flow and energy constraints.

The electricity market is modelled as a single purchaser that rewards all production at a flat rate. The resulting revenue estimates are then combined with scheme cost data to generate a range of standard investment measures (e.g. IRR, NPV, etc.).

B. *Monte-Carlo Simulations*

The software has been expanded to allow it to perform Monte-Carlo simulations of scheme operation under different climate scenarios (Fig. 2). It can generate and store a large number of synthetic precipitation and temperature series, and the statistical properties of the resulting river flows, production and financial measures may be extracted. Hence for a given climate scenario, estimates can be made of the IRR variance, project risk and the required rate of return. As only climate is varied between each simulation, the software does not perform full Monte-Carlo simulations. Rather, it enables the effects of climate change to be examined and isolated.

The synthetic series are produced using a periodic Markov model that estimates monthly values of each climate variable from the previous month's value, the statistical characteristics of that month and a normal random element, according to [8]:

$$v_{i,j} = \mu_j + \frac{\rho_j \sigma_j}{\sigma_{j-1}}(v_{i-1,j-1} - \mu_{j-1}) + t_i \sigma_j (1-\rho_j^2)^{0.5} \tag{3}$$

where v is the monthly climate variable to be predicted, μ and σ are the monthly mean and standard deviation respectively, ρ is the correlation coefficient between consecutive months, t is a random number, and i and j represent, respectively, the sequential and periodic indices.

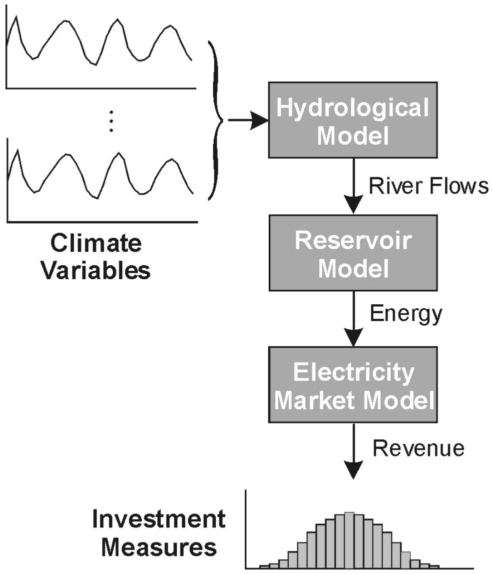

Fig. 2. Schematic of risk analysis process

V. Case Study: Batoka Gorge

The scheme chosen for the demonstration of this technique is the Batoka Gorge project, planned for the Zambezi River (Fig. 3), and used with the authors' previous work. The feasibility study [12] proposes the construction of a 1600 MW run-of-river plant to maximise system-wide firm power delivery and produce in the region of 9,100 GWh per annum. The software was found to provide a reasonable simulation of scheme operation and performance [3].

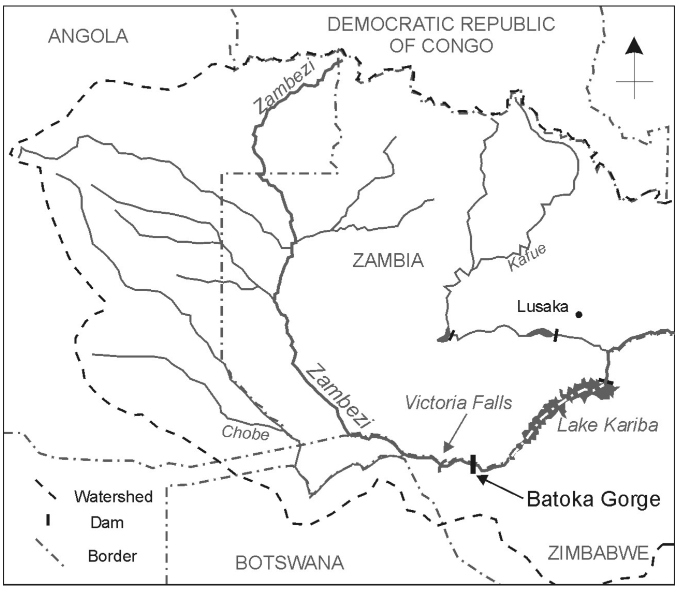

Fig. 3. Location of scheme within the Zambezi River Basin

A. *Validation of the Synthetic Series*

The monthly historic climate record (1961 to 1990) was extracted from the high-resolution global dataset compiled by New et al. [13] that consists of a range of climate variables (for 1901 to 1996). Analysis of the statistical properties of the precipitation and temperature series and the assumption of normal distributions, allowed five hundred pairs of thirty-year long precipitation and temperature series to be generated.

Before use, the synthetic series were examined to confirm that the series did, in fact, faithfully represent the original data. Table I shows the monthly mean and standard deviation for the original climate data and values averaged across the synthetic series. It can be seen that the statistics are similar, particularly so for temperature, and were therefore considered suitable for the purpose.

TABLE I
MEAN MONTHLY STATISTICAL PROPERTIES FOR ORIGINAL AND SYNTHETIC CLIMATE SERIES

Month	Precipitation (mm)				Temperature (°C)			
	Mean		Std Deviation		Mean		Std Deviation	
	Single	Synth.	Single	Synth.	Single	Synth.	Single	Synth.
Jan	193.61	193.51	25.74	25.35	23.63	23.63	0.59	0.59
Feb	171.24	171.01	30.14	30.04	23.59	23.58	0.51	0.51
Mar	136.13	136.18	39.66	39.32	23.54	23.54	0.57	0.56
Apr	42.08	42.20	21.29	20.58	22.45	22.46	0.50	0.50
May	2.35	2.86	3.41	2.69	19.86	19.87	0.99	0.98
Jun	0.24	0.34	0.48	0.35	17.31	17.31	0.85	0.86
Jul	0.00	0.40	0.00	0.57	16.95	16.94	0.70	0.69
Aug	0.80	0.95	1.05	0.85	19.76	19.76	0.81	0.80
Sep	7.57	7.60	3.17	3.14	23.29	23.28	0.49	0.49
Oct	42.72	42.49	16.40	16.24	24.93	24.93	0.60	0.59
Nov	115.31	114.72	29.95	29.98	24.31	24.31	0.80	0.78
Dec	183.61	183.45	28.25	27.82	23.70	23.70	0.58	0.58

B. *Performance under conditions of climate change*

To illustrate the use of the software in conducting climate risk analyses, three climate change scenarios were considered. Used previously in [3], two are from the output of the HadCM2 general circulation model (GCM) developed by the Hadley Centre (UK Meteorological Office). One, HadCM2-S, incorporates the effects of aerosols and correspondingly projects a slightly lower temperature change. The third scenario is from the ECHAM4 GCM developed at the German Climate Research Centre. Each scenario is a projection of conditions in the 2080s and detail changes in precipitation and temperature relative to GCM control runs representing conditions of no climate change. Table II shows the mean annual changes for the portion of the river basin upstream of the project.

TABLE II
MEAN ANNUAL CLIMATE CHANGES FOR THE 2080S

Climate Variable	GCM Scenario		
	ECHAM4	HadCM2	HadCM2-S
Precipitation (%)	−1.6	−12.5	−17.6
Temperature (°C)	+5.0	+5.3	+4.4

Simulations were carried out for every synthetic pair under historic conditions and with each of the three climate scenarios applied. The resulting statistical properties of a range of indicators were extracted and summarised in Table III. As mean values differ between scenarios, to allow meaningful comparison, the variance of each indicator is normalised and expressed as the coefficient of variation (CV). The following sections examine the results in greater detail.

TABLE III
SUMMARY OF RESULTS FROM MONTE-CARLO ANALYSIS (COEFFICIENT OF VARIATION IN PERCENT)

Measure	Base 1960-91			ECHAM4 2080s			HadCM2 2080s			HadCM2-S 2080s		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Precipitation (mm/month)	74.60	1.15	1.54	73.50	1.14	1.56	65.61	0.97	1.47	61.40	0.91	1.48
Temperature (°C)	21.94	0.03	0.16	26.96	0.03	0.13	27.27	0.03	0.13	26.33	0.03	0.14
River Flow (Mm^3/month)	3.17	0.10	3.07	2.85	0.09	3.05	2.29	0.06	2.73	2.05	0.05	2.63
Production (GWh/month)	783.37	10.77	1.38	734.17	10.63	1.45	654.23	10.75	1.64	613.18	12.83	2.09
IRR (%)	10.89	0.19	1.71	10.23	0.19	1.82	9.07	0.20	2.18	8.45	0.24	2.80

1) Variance of climate

The application of the GCM scenarios to the precipitation series alters the statistical properties of the series applied to the simulation tool. Other than the change in the average monthly mean, across the series, there are changes in average variance. As Table III shows, for both of the Hadley scenarios, the change in the standard deviation (16 to 20%) is larger than the mean change (2 to 18%, Table II), which consequently lowers the CV by up to 4.5% (i.e. lower variability). With a greater change in the mean, the ECHAM4 scenario delivers a 1% increase in CV. The reduction in variance can be seen in Fig. 4 with the precipitation distributions for both Hadley scenarios showing higher peak frequency.

Despite the significant rises in mean monthly temperature projected by the GCM scenarios, there is virtually no change in their standard deviation. Correspondingly, this lowers the CV for temperature by up to 20%.

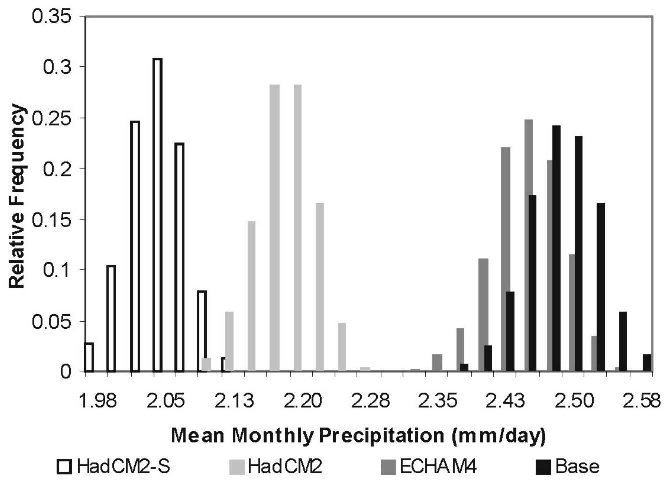

Fig. 4. Histogram of mean monthly precipitation

2) Variance of river flows

Each of the GCM scenarios causes significant decreases in river flows, with mean monthly flows falling by between 10% and 35% (Table III). The tendency of the river basin to amplify changes in precipitation is evident with mean flows altering by almost twice as much as precipitation. With even greater falls in standard deviation (11% to 45%), river flow CV decreases by up to 15% for the Hadley scenarios. The impact under the ECHAM4 scenario is limited to a 1% decrease in CV. Once again, the effects can be seen graphically in Fig. 5.

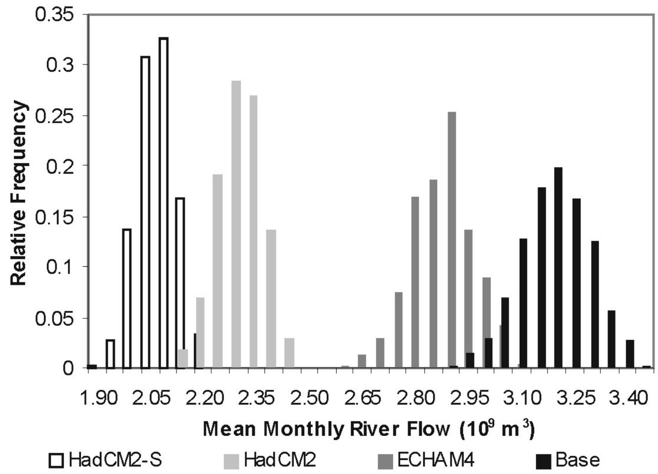

Fig. 5. Histogram of mean monthly river flow

3) Variance of production

Although relatively small, the integrating effect of the reservoir reduces the impact of the changes in river flows resulting in smaller decreases in production. Under the applied scenarios, mean monthly production falls by between 6% and 22% (Table III). As the standard deviation only changes significantly for the HadCM2-S scenario (19%), the CV rises under all GCM scenarios (5% for ECHAM4 and 52% for HadCM2-S). The large increase in variance under this Hadley scenario manifests itself in Fig. 6 as a noticeably flatter distribution.

4) Financial Risk Impacts

In line with the original study [3], energy production attracts revenue at a single rate ($30/MWh). Accordingly, sales income responds similarly to production, which in turn, impacts on the financial performance of the scheme. The financial indicator of primary interest is the internal rate of return (IRR), as it does not pre-select a discount rate and may be used to estimate changes in project beta. Mean IRR declines by between 6% for ECHAM4 and 22% for HadCM2-

S (Table III). The standard deviation of IRR across the scenarios reduces very slightly for the ECHAM4 scenario but increases by up to 27% for the Hadley scenarios. As such the scenarios deliver CV increases of between 6% and 64% with Fig. 7 showing the spread increasing with the degree of climate change. As such, the scenarios indicate an increased climate-related risk for which investors would expect to be compensated.

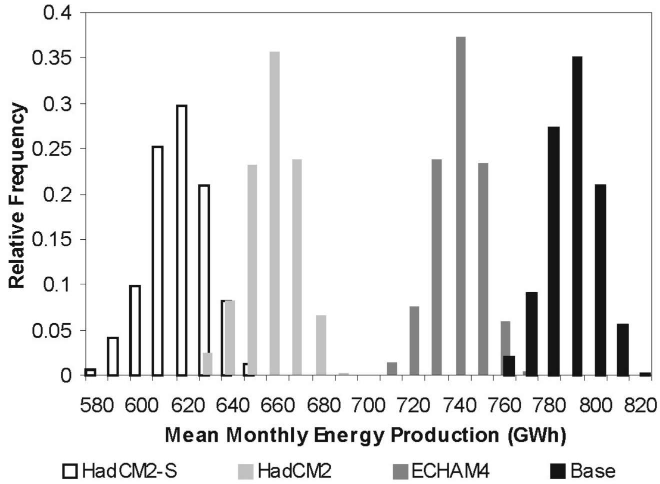

Fig. 6. Histogram of mean monthly energy production

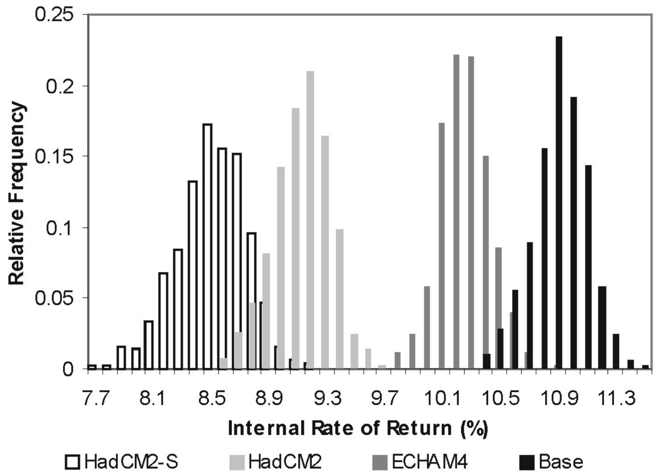

Fig. 7. Histogram of IRR under climate scenarios.

C. Required Rate of Return

Compensation for increased risk will manifest itself as an increase in the required rate of return for this hydroelectric scheme. There was no explicit report of risk analysis in the feasibility study, presumably as the scheme was planned for a non-liberalised market. Furthermore, without knowledge of the overall risk profile for the project, the authors are unable to confirm whether the increased climate-related risk will be sufficient to influence a would-be investor's choice of discount rate or the eventual decision about whether or not to proceed with the project. The development of a full Monte-Carlo simulation to include other project variables could satisfy this need. In the absence of this, however, a numerical example is presented below to illustrate the influence of climate-induced changes in risk on the expected rate of return for the project.

With the CAPM one may use the project beta to relate the expected rate of return to the project risk. Equation (2) expresses beta in terms of the equity and market risks. Here, however, only the climate component of the project risk can be measured. If we assume that the project beta is a linear function of project risk we can approximate (2) as:

$$\beta = k\sigma_p \tag{4}$$

where σ_p is the project risk (i.e. normalised standard deviation of project returns, IRR) and k is a constant. Further, project risk can be taken as the sum of all project risks and may be classified as climatic (σ_c) or non-climatic risks, yielding:

$$\beta = k((1-b)\sigma_p + \sigma_c) \tag{5}$$

where b is the proportion of total project risk that can be attributed to climatic factors. For a given pre-climate change project beta and relative climate risk contribution (b) we can estimate constant k. Hence, we may subsequently examine the effects of increased climate risk on the project beta and expected rate of return.

To illustrate this, consider a firm that would normally calculate or assign this scheme a project beta of 0.8 (i.e. less risky than its standard project). Further, we assume two different values for the climate risk contribution, b, of 10% and 33%. Finally, assuming that the risk-free and market rates of return are 5% and 10%, respectively, we may use (5) and the CAPM (1) to examine the consequences for the required rate of return of the increase in climate-related risk.

Table IV shows the project beta and required rate of return resulting from the application of the risk estimates from each GCM scenario to (5) and (1). It can be seen that the increased IRR variance raises both project beta and the required return and, as would be expected, the degree of change increases with the risk contribution. For example, with the larger risk contribution, the HadCM2-S scenario raises beta by 21% and the required rate of return by just over 9%. Here, we have only considered the case where the project is regarded as less risky than the average investment. For the opposite case ($\beta > 1$), the impact on the required rate of return would be greater.

TABLE IV
CLIMATE IMPACT ON PROJECT BETA AND REQUIRED RETURN

Scenario	10% Relative risk		33% Relative risk	
	Project beta	Required return (%)	Project beta	Required return (%)
Base	0.80	9.00	0.80	9.00
ECHAM4	0.81	9.02	0.82	9.08
HadCM2	0.82	9.11	0.87	9.36
HadCM2-S	0.85	9.25	0.97	9.85

This analysis is of relevance as the required rate of return determines whether the project is economically viable: where IRR exceeds the required rate, the project will be considered economic and vice versa. In Table IV, the risk-adjusted required rate of return is seen to *rise* for all GCM scenarios.

However, Table III shows the IRR to *fall* for all scenarios. Under both Hadley scenarios the adjusted required rate of return exceeds the mean return from the scheme. The appraisal criteria state that, under these conditions, the scheme would be non-economic. Applying the initial, non risk-adjusted required return (9%) would have seen the project deemed non-economic under only the more extreme HadCM2-S scenario. Hence, the explicit inclusion of climate-related risk influences the investor's decision regarding this project.

D. Comparison with Single Values

The results of the Monte-Carlo simulations may be used to examine whether the financial performance simulated by [3], for a single climate series, is unduly optimistic. With statistical similarity between the original climate data and the synthetic series, it would be reasonable to expect that the mean results from the Monte-Carlo simulation would be similar to the single values. As Table V shows, the Monte-Carlo simulation indicates a mean financial performance that is inferior to the single series values. The mean IRR is around 1% lower and up to 2.3% lower for the base and GCM scenarios, respectively. While relatively small, these differences indicate the potential for optimistic projections using single time series, particularly where additional variables are included in the simulation.

TABLE V
IRR WITH MONTE-CARLO AND SINGLE VALUE SIMULATIONS

Scenario	Single Value	Monte-Carlo
Base	11.00	10.89
ECHAM4	10.35	10.10
HadCM2	9.25	9.07
HadCM2-S	8.65	8.45

VI. DISCUSSION

The theoretical basis for this study is that the non-linear behaviour of river basins will result in changes in both the mean and the variance of river flows as a result of changes in mean precipitation alone. Furthermore, it was hypothesised that these changes in variance would feed through and alter the variance of project returns and in consequence the project risk. The simulations confirm that changes in climate will result in a change in the financial risk faced by hydroelectric schemes. They also suggest that the degree of risk is linked to the magnitude of precipitation change and that risk appears to increase as precipitation decreases. A sensitivity study confirms this: a 10% reduction in precipitation raises risk by over 17%; temperature rise also increases risk, albeit by a smaller amount (e.g. a 2°C rise delivers a 2.5% increase).

As the simple numerical example illustrates, the application of the risk estimates to the CAPM highlights a discernible impact on the required rate of return. To compensate for the increased risk and to maintain the interest of the investor, the financial return from the scheme would have to continue to meet or exceed the increased required rate of return. In the scenarios used here, the expected return decreases, in some cases to the extent that it now lies below the newly raised threshold, thus rendering the scheme non-economic. Essentially, adjusting the required rate of return to reflect the increased risk degrades the margin between the expected and minimum acceptable scheme performance, reducing the likelihood of investment.

Clearly, a more explicit exploration of these issues requires a detailed examination of the role of climate within the overall risk profile of the project. Overall, however, in quantifying the relationship between climate change and project risk, the study reinforces the perception that with the prospect of climate change there will be major challenges for the encouragement of investment in future hydropower projects.

The scenarios presented here represent only a small number of the many possible climate change scenarios that may result in temperature changes in the range suggested by climate models [14]. More importantly, the precipitation changes that accompany the temperature rise include some that predict increased precipitation for this region. The determination of an expected scenario of change is rather subjective, as the assignment of probabilities to climate change scenarios is uncertain. The authors consider that as subjectivity will remain a factor of investment decision-making, climate scenarios will be a useful addition to risk appraisal.

These scenarios should be regarded as 'worst case' for several reasons: climate change is considered in isolation, that climate has undergone a step change and that scheme operational practice is static. More realistic results could be achieved with conditions that change over time.

VII. CONCLUSIONS

Previous studies have indicated that hydropower economics are sensitive to changes in precipitation and temperature. The studies also found that, in addition to mean changes, there were changes in the variance of production and sales revenue. This study aimed to determine whether such changes would lead to alterations in the financial risk faced by the project, given that perceptions of risk play a major part in project appraisal.

Using a case study, a Monte-Carlo analysis was carried out using synthetic precipitation and temperature time series that were generated from the historic climate record. The application of several climate change scenarios to the synthetic series allowed an examination of the influence of climate on the magnitude and variance of financial returns.

The simulations found that, for the climate change scenarios used, there were increases in the variance of the financial returns and therefore an increased risk. Without explicit knowledge of the overall risk profile of the study scheme it was not possible to say whether the changes in climatological risk would alter the investment decision. However, a numerical example indicated that the increased risk raises the project beta and the required rate of return. It is apparent that climate change has the potential to be doubly damaging for hydropower with the alteration of both the expected return from hydroelectric installations and the financial risk that they face.

While the analysis presented here does not provide a precise prediction of the future, the authors believe that the results of this study indicate a further, potentially serious, issue for hydroelectric projects. They also believe that there is merit in applying a refined version of the methodology in other regions to develop a fuller picture of the prospects for hydroelectric exploitation.

VIII. DEDICATION

On the 11th March 2002, during the final drafting of this work, Professor Bert Whittington was tragically killed in a road accident in Edinburgh. He was aged 56 and leaves his wife Helen and two sons, Barry and Alan. A tremendous loss to his family, friends and colleagues, Bert Whittington will be remembered as the highly intelligent, witty and talented man that he was and for the inspiration and good humour that he gave to others.

IX. ACKNOWLEDGEMENTS

The authors wish to thank the Zambezi River Authority for their permission to use and publish data relating to the Batoka Gorge scheme, and also Knight Piésold Ltd (Ashford, UK) for their assistance in obtaining the material. The monthly climate time-series data was supplied by the Climate Impacts LINK Project (UK Department of the Environment Contract EPG 1/1/16) on behalf of the Climatic Research Unit, University of East Anglia.

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